Energy, Mines and Resources Canada

Hon. Marcel Masse, Minister

Énergie, Mines et Ressources Canada

L'Hon. Marcel Masse, Ministre

Canada

PRELIMINARY INVESTIGATION OF THE POTENTIAL EFFECTS OF ICING ON WIND ENERGY SYSTEM PERFORMANCE

PREPARED FOR

RENEWABLE ENERGY BRANCH
ENERGY, MINES AND RESOURCES CANADA
OTTAWA, CANADA
DSS File No. 54SZ.23216-6-6119

PREPARED BY

R. KOLOMEYCHUK AND A. SILIS
THE ENVIRONMENTAL APPLICATIONS GROUP LIMITED
6126 YONGE STREET, 2nd FLOOR
WILLOWDALE, ONTARIO
M2M 3W7
(416) 224-0701

SCIENTIFIC AUTHORITY
MONIQUE CARPENTIER, P.Eng.
TECHNOLOGY COORDINATOR - WIND ENERGY
RENEWABLE ENERGY BRANCH
ENERGY, MINES AND RESOURCES
460 O'Connor Street
OTTAWA, ONTARIO
K1A 0E4

89-05627/

RÉSUMÉ

Une enquête préliminaire au sujet des effets possibles du givrage sur les systèmes de conversion de l'énergie éolienne (SCEE) a été entreprise pour les régions arctiques, subarctiques et côtières du Canada. En particulier, une analyse du verglas et du givrage possible a été faite pour quelques endroits sélectionnés dans les régions géographiques mentionnées ci-dessus. La perte possible d'énergie éolienne a été déterminée au cours du givrage et subséquemment lorsque la température demeurait au-dessous du point de congélation. On suppose que le givre pourrait rester sur un SCEE si la température de l'air est inférieure à 0°C. Les données utilisées pour ces analyses proviennent des archives climatiques du Service de l'environnement atmosphérique. Ces données ont été transmises à un micro-ordinateur anguel on a recoura pour effectuer l'extraction des données et les calculs.

La durée moyenne des précipitations de verglas pour toutes les stations est seulement de 2 à 4 heures; cependant, après les précipitations, les températures restaient au-dessous de zéro de 10 à 20 heures en moyenne. Le brouillard surfondu (surfusion dans les nuages) présente une situation semblable.

L'analyse préliminaire des pertes d'énergie possibles causées par le givrage indique qu'une proportion allant jusqu'à 10 % de l'énergie possible disponible pourrait être influencée par le givrage. Dix des 25 endroits étudiés présentaient des pertes d'énergie possibles de 4 % ou plus. Ces chiffres sont très prudents pour plusieurs raisons. La raison principale est que les stations météorologiques sont situées dans des terres basses et ne peuvent fournir de données représentatives pour les conditions plus rigoureuses des altitudes plus élevées.

Un dernier volet de l'étude portait sur la capacité du rayonnement solaire de faire fondre le givre. Les résultats portent à croire que les périodes de givre seraient considérablement réduites si les pales de rotor étaient noires.

Les résultats de l'étude indiquent que les données des stations aérologiques pourraient servir pour l'analyse des effets du givrage en altitude. On ne connaît pas les effets réels du givrage sur le rendement d'un SCEE. Des données de ce genre sont souhaitables si des éoliennes doivent être installées dans des régions sujettes au givrage.

SUMMARY

A preliminary investigation of the potential effects of icing on wind energy conversion systems (WECS) was undertaken for the Arctic, sub-Arctic and coastal areas of Canada. Specifically, an analysis of freezing rain and potential in-cloud icing was conducted for selected locations in the above geographic regions. Potential wind energy loss was determined during icing events and afterwards if the temperature remained below freezing. It is assumed that the ice would remain on a WECS if the air temperature was less than 0°C. The data used for the analysis were obtained from the Atmospheric Environment Service's climatic archive. These data were transferred to a microcomputer which was used to perform data extraction and calculations.

The mean duration of freezing precipitation events for all stations ranges only from 2 to 4 hours; however, the duration of temperatures less than zero after an event ranged in average from 10 to 20 hours. A similar situation exists for supercooled fog (in-cloud icing condition).

The preliminary analysis of potential energy loss due to icing indicated that up to 10 percent of potential available energy could be affected by icing. Of the 25 locations investigated, ten had potential energy losses of 4 percent or more. These are conservatively low figures for several reasons. Most importantly, meteorological stations are situated in low-lying areas which do not provide representative data of the more severe conditions at higher elevations.

A final component of the study investigated the ice-melting capability of solar radiation after an icing event. The results suggest that black-coated rotor blades would tend to keep the ice residence time down substantially.

The results of the study indicate that the altitude effects of in-cloud icing should be investigated using data from upper air stations. The actual effects of icing of WECS performance are not known and observations of this kind are warranted if wind turbines are to be located in ice-prone regions.

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1. INTRODUCTION

1.1 GENERAL

The more promising geographical regions of Canada for utilization of wind energy conversion systems (WECS) are isolated communities in Arctic, sub-Arctic, and coastal areas. In these parts of the country, the available wind energy can be sufficient to be a potential fuel-saver for diesel generation installations. Little work has been done to investigate what effects atmospheric icing will have on the performance of WECS in these regions. In addition little information exists from which to quantify the effects of ice accumulation on wind turbine performance and behaviour.

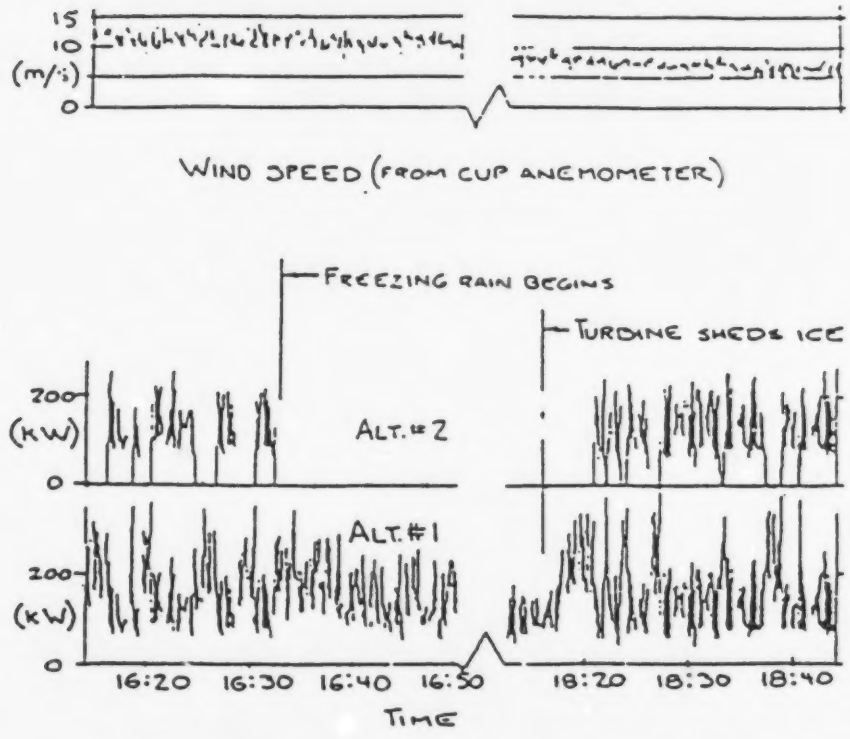
Chappel and Templin (1985) have indicated that very little ice accumulation, in the order of 2 or 3 mm, is sufficient to reduce power output significantly. A short freezing rain episode on the 500 kW AQUILO vertical axis wind turbine (VAWT) on Prince Edward Island illustrates (Figure 1) the dramatic reduction in power observed (ibid, 1985). A hazardous condition might also occur if an anemometer, controlling a WECS, had its speed decreased while the turbine passed its cutout speed. Anemometer slowdown is also indicated in Figure 1. This study examined the potential of energy reductions as a result of ice accumulation on a turbine using climatic data.

1.2 BACKGROUND INFORMATION ON ATMOSPHERIC ICING

Atmospheric ice formation on structures occurs by droplet or particle accretion. Freezing precipitation and in-cloud icing result in the formation of rime or glaze ice. The form of the ice is governed by the temperature of the droplets, their size and the rate at which they strike a surface. Glaze icing occurs predominantly during freezing precipitation and has a density of about 0.9 g/cm^3. Rime deposits occur when structures are exposed in cold fogs or clouds. Ice density in this case is usually in the range of 0.1 to 0.6 g/cm^3.

Freezing rain is most commonly associated with the passage of a warm front. This condition will usually not last more than several hours and is confined to a narrow sweeping band associated with the warm front. The severity and frequency of glaze ice depends on topography, the proximity of moisture sources and the preferred path of storms. Another type of freezing rain know to occur, but far less common, is the case of rain falling through a cold air mass trapped in an enclosed valley. In-cloud icing, resulting from accretion of supercooled fog or cloud droplets, is usually most severe in regions close to large bodies of water, and in coastal ranges.

FIGURE 1
AN ICING EPISODE ON 500 kW VAWT (AQUILO)
PRINCE EDWARD ISLAND, FEB. 13 1985



SOURCE: CHAPPELL + TEMPLIN, 1985

The actual shape of an ice deposit on a rotor blade is of importance. During glaze icing, drops or droplets do not freeze immediately on impact but run a distance before freezing. The resulting ice deposit shape in this case would likely increase drag. With rime icing, water droplets freeze immediately on impinging on the leading edge of an aerofoil but it is not immediately apparent what effect icing would have. For example, this type of accretion in minor amounts may not necessarily affect the aerodynamic characteristics of the rotor at all; or may, due to an increase in the chord, result in an increase in lift (Mortimer, 1980); or may possibly modify the leading edge geometry sufficiently to disturb the whole flow field which could result in lift decrease and drag increase. Once ice accumulation exceeds some unspecified amount, there will likely be some effect on performance.

Large amounts of glaze or rime ice accretion could be a possible cause of dynamic imbalance as ice chunks are released from the turning rotor. The preliminary standard specified by the Canadian Standards Association (CSA, 1985) stipulates that the design of a small WECS shall consider a minimum ice build-up of 60 mm, with a density of 900 kg/m^3.

1.3 PROJECT OBJECTIVES

An analysis of freezing rain and potential in-cloud icing was undertaken for selected locations in the Arctic, sub-Arctic, and coastal areas of Canada in order to investigate potential performance degradation of WECS in these areas. A realistic appraisal of wind energy system downtime due to icing would provide the basis for refined wind resource assessments. The study was undertaken to provide a preliminary evaluation of the significance of icing in the above mentioned locations in Canada.

2.0 METHODS

2.1 DATA SOURCE

The primary objective in weather observing station selection was to obtain meteorological data representative of coastal, Arctic and sub-Arctic regions of Canada. The selected locations are provided in Figure 2. Once this task was completed hourly climatic data for the selected observing stations were obtained from the Atmospheric Environment Service archives for the selected locations. The ten-year period 1967-76 was used in the project since the Atmospheric Environment Service has prepared a wind climatology using the same time interval (Morris and Howell, 1984).

2.2 DATA ANALYSES

Data analyses were conducted, on a microcomputer, under three major categories:

1. icing event occurrence and duration
2. duration of temperatures less than 0°C after an event
3. solar radiation after an event

The number of hours of freezing precipitation (freezing rain and freezing drizzle combined) were compiled for each station along with the frequency of duration of the events. Potential icing due to supercooled fogs or clouds was considered to have occurred when air temperature was less than 0°C, visibility was less than 1 km, and fog was present.

The visibilitycriterion chosen was rather arbitrary due to lack of definitive relations between visibility and liquid water content. For inland radiation fog, a visibility of 1 km may be associated with a liquid water content of about .01 g/m^3 (e.g. Pinnick et al., 1978) whereas the corresponding liquid water content for coastal advection fog may be in the order of .04 g/m^3 (Kumai, 1973). The liquid water content (LWC) in the air is of great importance to the amount of ice accreted.

The amount of water captured by a unit length of a blade per unit time can be written as (after Gustafsson et al., 1982)

$$Wm = LWC \times h \times F \times V$$

where Wm = mass of captured water
h = thickness of blade measured perpendicular to V
F = efficiency of catch (collection efficiency) i.e. ratio of water captured to water in the air

Collection efficiencies calculated by Langmuir and Blodgett (1946) show that F increases rapidly as drop radius and wind speed increase. As the blade thickness increases the efficiency

Figure 2
LOCATIONS OF WEATHER OBSERVING STATIONS SELECTED FOR DATA ANALYSIS
KEY
STATION LOCATIONS
ARCTIC OCEAN
BEAUFORT SEA
BAFFIN BAY
CAPE PARRY
CAMBRIDGE BAY
BURWASH
HALL BEACH
FROBISHER BAY
YELLOWKNIFE
BAKER LAKE
HUDSON BAY
KUUJUAQ
PRINCE RUPERT
SMITHERS
PORT HARDY
THOMPSON
KUUJJUARAPIK
NITCHEQUON
DANIELS HARBOUR
GANDER
ST. JOHN'S
SEPT-ILES
STEPHENVILLE
BIG TROUT LAKE
JAMES BAY
ABBOTSFORD
GRINDSTONE ISLAND
SYDNEY
CHATHAM
SUMMERSIDE
ATLANTIC OCEAN
YARMOUTH

decreases. Considering a hypothetical blade thickness of.05 m, a collection efficiency of 0.5, a blade velocity of 25 m/s, and a liquid water content of 0.01 g/m^3, results in 0.006 g/sec being deposited over a 1 metre blade length. In a one-hour period, this would accumulate to about 22.5 grams or a thickness of about 1 mm if the accumulated ice density is in the vicinity of 600 kg/m^3. A one millimetre thickness might be considered as possibly affecting WECS performance in light of the observations of Chappell and Temlin (1985) referred to in Section 1.1.

Occurrence and duration statistics were compiled by the month and for the total period of record. For monthly values, an event begun in one month and ending in another was assigned to the month in which it began.

For each icing event defined in the preceding methodology, the length of time, in hours, for which the temperature remained below zero after icing was determined. This duration and the icing duration provide the total amount of time that a wind energy turbine might be affected by icing. The potential wind energy density lost during these periods was calculated on an hourly basis according to (Morris and Howell, 1984):

$$P_d = 0.037355\ PV^3/(T + 273.15)$$

$$E = P_d\ S \times 10^{-6}$$

where

P_d is the wind power density (Wm^{-2})
P is the atmospheric pressure (kPa)
V is the wind speed (kmh^{-1})
T is air temperature (°C)
E is the wind energy density (MJm^{-2})
S is the duration of the period (seconds)

The parameters P, V, and T were obtained directly from the hourly AES climatic records and used to calculate wind energy density. These equations account for the rate at which kinetic energy in the wind stream is delivered perpendicular to a unit area. The actual amount of energy that can be extracted from the wind stream depends on the wind speed distribution and the characteristics of the WECS. The relations do provide a method of characterizing the available wind power (or as in the present case wind energy lost due to icing) of various sites. The wind speeds obtained from AES although nominally one-minute mean speeds observed on the hour are used as one-hour mean values in the above relation.

Potential average annual wind energy lost due to icing was compared with potential available average annual wind energy values provided by the Atmospheric Environment Service (R. Morris, pers. comm.). The Atmospheric Environment Service wind energy data were adjusted to a standard 10-metre height above

ground. Hence, the comparisons need to be qualified for stations, used in the present analyses, where wind speeds are measured at higher elevations. In this case, the wind energy potential lost due to icing relative to the total available would be lower than the analyses indicate; however, only a relatively few stations are affected and usually for only short periods as indicated below:

Frobisher Bay	13.1 m from beginning to 09/68
St. John's	19.8 m from beginning to 07/69
Sept-Iles	18.6 m from beginning to 09/67
Swift Current	13.1 m from beginning to 02/70
Thompson	13.1 m for entire 10-year period

The final analyses comprised of determining the mean profile of hourly global solar radiation and ambient air temperature after an icing event. (Global solar radiation refers to the sum of direct beam, diffuse sky and ground reflected radiation.) This analyses was restricted to the cases when air temperature was less than 0°C and was compiled on an annual basis. The purpose of this analyses was to compare the relative natural deicing rates of black coated and aluminum blades.

Energy transfer to an unheated de-icing surface on a WECS involves the following quantities:

Heat loss by convection
Heat loss by sublimation
Heat gained from frictional heating in boundary layer
Heat gained from solar radiation

Neglecting convection, Stallabras (1981) calculated that approximately 0.37 MJ/m would be required to melt 1 mm of ice at -10°C on a 24-inch chord NACA 0018 blade. He indicates that the required energy would more likely be in the order of 1MJ/m if convection and conduction losses are considered. In terms of energy density, approximately 0.5 MJ/m^2 would be required to melt ice at -10°C. At an ambient temperature of -3°C, the heat requirement would be reduced to the order of 0.15 MJ/m^2. In order for solar radiational heating to be effective, the structure must be painted black.

The absorptivity of black paint is about 0.95 compared with about 0.1 for oxidized aluminum. The albedo of glaze ice is in the range of 0.2 to 0.4. Therefore approximately 70 percent of the solar radiation would be available for heating with a black blade compared with less than 10 percent for a aluminum blade. For rime icing, the albedo approaches that of snow or approximately 0.8. Thus, only about 20 percent of the solar radiation would be available in this case; however, rime ice is not likely to deposit evenly over the blade. Parts of the blade

would be exposed and absorb solar radiation readily if painted black. Overall, the total energy requirement for natural deicing by solar radiation with a black-coated blade should be in the order of 0.2 MJ/m^2 while a aluminum blade would require about 2 MJ/m^2. In all cases, the solar radiation required to melt ice is normal incidence.

3.0 DATA ANALYSES RESULTS

3.1 ICING EVENT OCCURRENCE AND DURATION

3.1.1 Freezing Precipitation

The annual characteristics of the freezing precipitation events at the various locations are provided in Table 1. The mean duration of freezing precipitation events for all stations range only from 2 to 4 hours; however the duration of temperatures less than zero after an event range from 3 hours at Port Hardy to 65 hours at Fort Chimo. Gander had the largest number of freezing precipitation events over the ten year period (352) and the largest number of hours of freezing precipitation (1343) while the least was recorded at Port Hardy (4 events for a total of 14 hours). The distribution frequency of events and hours over the ten-year analysis period is provided below:

NUMBER OF EVENTS				
0-50	51-100	101-200	201-300	301-400
6	6	12	1	2

NUMBER OF HOURS			
0-200	201-600	601-1000	1000-1400
12	12	1	2

After freezing precipitation events, the potential residence time of ice varied (as indicated by air temperatures below 0°C) varied greatly among stations. The percentage of freezing precipitation events followed by freezing temperatures periods varied from 25 % at Port Hardy to 83 % at Cambridge Bay. The largest number of post events occurred at Cape Parry (202) and the largest number of hours was also recorded at this location (4728). The distribution frequency of post events and hours for the selected locations is given in the following:

NUMBER OF EVENTS				
0-50	51-100	101-200	201-300	301-400
8	12	5	1	0

NUMBER OF HOURS				
0-200	201-600	601-1000	1001-1400	>1400
3	5	3	6	9

The total number of hours in a ten-year period is 87603. Over 6 percent of the time, freezing precipitation or ice may be present at Gander or Cape Parry. At 4 percent, the location list can be increased to include St. John's and Fort Chimo. Only the locations in British Columbia and Burwash in the Yukon have occurrence levels less than 1/2 percent.

TABLE 1

FREEZING PRECIPITATION

	EVENT			POST EVENT			
	Mean Duration (hr)	No. of Events	Total No. of Hours	Mean Duration (hr)	No. of Events	Percent*	Total No. of Hours
St. John's	4	335	1310	17	162	48.4	2817
Gander	4	352	1343	17	196	55.7	3396
Daniels Harbour	2	106	243	16	46	43.4	755
Stephenville	2	101	199	11	46	45.5	495
Cartwright	2	170	416	14	116	68.2	1668
Sydney	3	193	637	15	79	40.9	1149
Yarmouth	3	76	215	16	39	51.3	607
Chatam	3	163	514	10	91	55.8	930
Summerside	2	186	409	11	108	58.1	1212
Grindstone	2	187	457	11	94	50.3	1021
Sept Iles	3	104	341	9	64	61.5	562
Fort Chimo	2	81	170	65	59	72.8	3850
Kuuj	2	100	183	24	64	64.0	1514
Yellowknife	4	126	452	21	86	68.3	1801
Baker Lake	2	81	195	15	60	74.1	895
Hall Beach	2	75	142	21	61	43.0	1258
Cape Parry	2	271	579	23	202	74.5	4728
Cambridge Bay	3	138	354	20	115	83.3	2310
Frobisher Bay	2	31	72	20	22	71.0	444
Burwash	2	13	27	30	7	53.8	211
Thompson	3	140	36,	14	99	70.7	1399
Nitchequon	2	84	175	22	54	64.3	1191
Big Trout Lake	2	123	266	19	95	77.2	1807
Smithers	2	25	59	20	20	80.0	403
Prince Rupert	3	10	27	9	6	60.0	56
Abbotsford	4	41	158	4	22	53.7	85
Port Hardy	4	4	14	3	1	25.0	3

* percent of icing events that were followed by a period where air temperatures were < 0°C.

Monthly the occurrences of freezing precipitation vary with geographic location. For the sub-Arctic locations, such as Yellowknife and Nitchequon, the greatest frequency of events occurs during November and December. In the Arctic, the frequency of occurrence is bimodal with the greatest frequencies occurring during April or May and October or November. The pattern in the Maritimes has peak occurrence during the months January through March. At all stations, with the exception of Cape Parry there were no or rare occurrences (1 or 2) of freezing precipitation during July or August.

3.1.2 Supercooled Fog

The annual characteristics of supercooled fog events and post events (air temperature less than 0°C) are provided in Table 2. The mean duration of events is confined to a narrow range of 2 to 3 hours with the exception of Port Hardy which has a one hour mean duration. The mean duration of temperatures less than zero after an event ranges from 6 hours at Prince Rupert, Abbotsford, and Burwash to 69 hours at Fort Chimo. St. John's had the largest number of events of supercooled fog over the ten year period (247) and the largest number of supercooled fog hours (788). Port Hardy has the least number of events (4) and hours of occurrence (4). The distribution frequency of events and hours of occurrence over the ten-year period is provided in the following (the intervals used for freezing precipitation have been retained for supercooled fog):

NUMBER OF EVENTS

0-50	51-100	101-200	201-300	301-400
13	5	8	1	0

NUMBER OF HOURS

0-200	201-600	601-1000	1000-1400
17	9	1	0

After a supercooled fog event, temperatures are more likely to remain below freezing than for a freezing precipitation event. The percentage of supercooled fog events followed by freezing temperatures varies from 50 percent at Port Hardy to 100 percent at Cambridge Bay. The largest number of post events occurred at St. John's; however, the largest number of hours was observed at Fort Chimo (4876). The distribution frequency of event occurrence and hours for the stations in Table 2 is provided below:

NUMBER OF EVENTS

0-50	51-100	101-200	201-300	301-400
13	6	8	0	0

NUMBER OF HOURS

0-200	201-600	601-1000	1001-1400	>1400
3	7	5	3	9

TABLE 2

SUPERCOOLED FOG

	EVENT			POST EVENT			
	Mean Duration (hr)	No. of Events	Total No. of Hours	Mean Duration (hr)	No. of Events	Percent*	Total No. of Hours
St. John's	3	247	788	11	157	63.6	1788
Gander	2	135	310	14	109	80.7	1501
Daniels Harbour	2	24	42	15	21	87.5	324
Stephenville	2	21	43	15	20	95.2	300
Cartwright	2	66	149	12	63	95.5	751
Sydney	3	110	282	11	103	93.6	1105
Yarmouth	2	43	204	19	37	74.4	615
Chatam	2	49	110	10	44	89.8	422
Summerside	2	51	90	16	51	100.0	830
Grindstone	3	108	286	20	96	88.9	1900
Sept Iles	2	209	244	12	108	99.1	1300
Fort Chimo	2	75	185	69	71	94.7	4876
Kuuj	2	91	200	17	80	87.9	1350
Yellowknife	3	90	258	18	78	86.7	1441
Baker Lake	3	50	137	16	47	94.0	772
Hall Beach	3	141	403	13	122	86.5	1578
Cape Parry	3	176	532	13	152	86.4	1998
Cambridge Bay	3	117	329	17	113	100.0	1967
Frobisher Bay	2	33	82	15	31	99.0	477
Burwash	3	18	52	6	13	72.2	73
Thompson	2	47	109	114	42	89.4	604
Nitchequon	2	33	78	12	26	78.8	304
Big Trout Lake	2	22	51	12	22	100.0	261
Smithers	3	160	429	11	158	98.8	1724
Prince Rupert	2	33	51	6	28	84.8	167
Abbotsford	2	47	96	6	40	85.1	231
Port Hardy	1	4	4	25	2	50.0	50

* percent of icing events that were followed by a period where air temperatures were < 0°C.

Only one station, Fort Chimo, has more than 4 percent occurrence of supercooled fog and potential ice presence compared with four stations for freezing precipitation. Daniels Harbour, Cartwright, Burwash, Nitchequon, Big Trout Lake, Prince Rupert, Abbotsford, and Port Hardy have less than 0.5 percent level of occurrence.

The monthly variation of supercooled fog occurrence is similar to that of freezing precipitation (refer to Section 3.1.1).

3.2 POTENTIAL WIND ENERGY LOSS FROM ATMOSPHERIC ICING

Potential wind energy lost during and following icing events in periods of freezing temperatures are provided in Table 3. The potential average annual wind energy density available at these sites are provided for comparison. In all cases, the largest potential loss of energy occurs from ice residence after an icing event. For example, at Gander, 314 MJ/m^2 of annual average energy may be lost after freezing precipitation events compared with 147 MJ/m^2 during an event. At the same location, potential energy lost from supercooled fog icing is 18 MJ/m^2 compared with 195 MJ/m^2 after events from ice adherence.

The largest amount of potential energy lost, 1323 MJ/m^2 occurred at Grindstone Is. which represented 5.1% of the total available energy at this site. There is no overall trend by region for the percentage of potential energy lost by icing causes. For example in the Maritimes, power lost varies from as little as 1.3 percent at Daniels Harbour to 10.2 percent at Gander. Similarly, in the Arctic, lost power ranges from 0.1 percent at Burwash to 8.4 percent at Cape Parry. Overall, power loss in British Columbia is small but so is the potential available energy at these four locations.

The seasonal variation of potential wind energy loss from freezing precipitation and supercooled fog events are provided in Tables 4 and 5, respectively. Both freezing precipitation and fog follow the same monthly pattern and tend to peak together.

3.3 SOLAR RADIATION AVAILABLE AFTER AN ICING EVENT

The mean solar radiation and air temperature after an icing event for the various locations are provided in Appendix I. In this section information is provided for St. John's, Gander, Grindstone Island, Cape Parry, and Cambridge Bay. These locations have the highest potential wind energy losses due to icing of the stations analyzed.

After a freezing precipitation event, when temperatures

TABLE 3

ANNUAL AVERAGE WIND ENERGY (MJ/m^2)

	During Freezing	Post Precipitation	During Supercooled	Post Fog	Total	Potential All Hours	% Lost
St. John's	221	494	58	250	1023	10872	9.4
Gander	147	314	18	195	674	6605	10.2
Daniels Harbour	63	95	2	44	204	15584	1.3
Stephenville	25	50	1	15	91	6019	1.5
Sydney	72	116	12	140	340	6889	4.9
Yarmouth	31	52	3	91	177	5806	3.0
Chatam	11	36	1	21	69	2613	2.6
Summerside	51	154	2	85	292	6661	4.4
Grindstone	208	457	16	642	1323	26066	5.1
Sept-Iles	34	54	20	155	263	4289	6.1
Kuujjuarapik	15	110	8	96	229	5418	4.2
Yellowknife	10	65	2	40	117	3037	3.9
Baker Lake	29	131	11	67	238	11622	2.0
Hall Beach	16	177	17	294	504	11142	4.5
Cape Parry	34	460	33	105	632	7507	8.4
Cambridge Bay	42	377	25	336	780	12388	6.3
Frobisher Bay	5	21	1	25	52	4387	1.2
Burwash	1	1	<1	<1	2	2927	0.1
Thompson	10	36	2	17	65	2060	3.2
Nitchequon	12	53	1	8	74	3816	1.9
Big Trout Lake	13	84	1	7	105	3082	3.4
Smithers	<1	1	<1	4	5	726	0.6
Prince Rupert	<1	3	1	2	6	4188	0.1
Abbotsford	3	1	<1	1	5	2115	0.2
Port Hardy	7	5	1	8	21	3416	0.6

TABLE 4
POTENTIAL WIND ENERGY LOST BY MONTH
DURING AND AFTER FREEZING PRECIPITATION EVENTS

Location	Percent of Annual Average Wind Density											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
St. John's	28	10	22	18	7	0	0	0	0	*	1	14
Gander	25	15	17	19	3	0	0	0	0	2	6	13
Daniels Harbour	29	26	11	6	1	0	0	0	0	*	4	23
Stephenville	28	21	21	5	0	0	0	0	0	0	1	24
Sydney	27	15	34	14	*	0	0	0	0	0	*	10
Yarmouth	9	37	23	*	0	0	0	0	0	0	0	31
Chatam	14	14	13	7	0	0	0	0	0	0	31	21
Summerside	30	15	17	2	0	0	0	0	0	0	*	36
Grindstone	23	11	28	5	*	0	0	0	0	0	1	32
Sept-Iles	20	5	11	43	*	0	0	0	0	1	3	16
Kuujjuarapik	15	2	4	15	20	2	0	0	*	1	38	3
Yellowknife	*	1	6	2	12	0	0	0	0	40	35	4
Baker Lake	0	0	0	2	23	13	0	0	2	29	29	2
Hall Beach	0	0	0	*	10	6	*	0	29	49	5	1
Cape Parry	1	*	*	*	28	3	*	3	19	43	2	1
Cambridge Bay	0	0	0	4	15	13	0	0	19	45	4	0
Frobisher Bay	0	0	0	2	16	*	0	0	0	69	13	0
Burwash	0	0	0	0	0	0	0	5	2	48	39	6
Thompson	7	2	2	14	4	1	0	0	*	6	42	23
Nitchequon	8	2	12	8	*	0	0	0	0	40	24	6
Big Trout Lake	2	1	7	9	8	0	0	0	*	6	63	5
Smithers	15	6	0	0	0	0	0	0	0	0	18	60
Prince Rupert	71	0	0	0	0	0	0	0	0	0	26	3
Abbotsford	65	21	0	0	0	0	0	0	0	0	2	12
Port Hardy	99	0	0	0	0	0	0	0	0	0	0	1

* indicates less than 0.5 %

TABLE 5
POTENTIAL WIND ENERGY LOST BY MONTH
DURING AND AFTER SUPERCOOLED FOG EVENTS

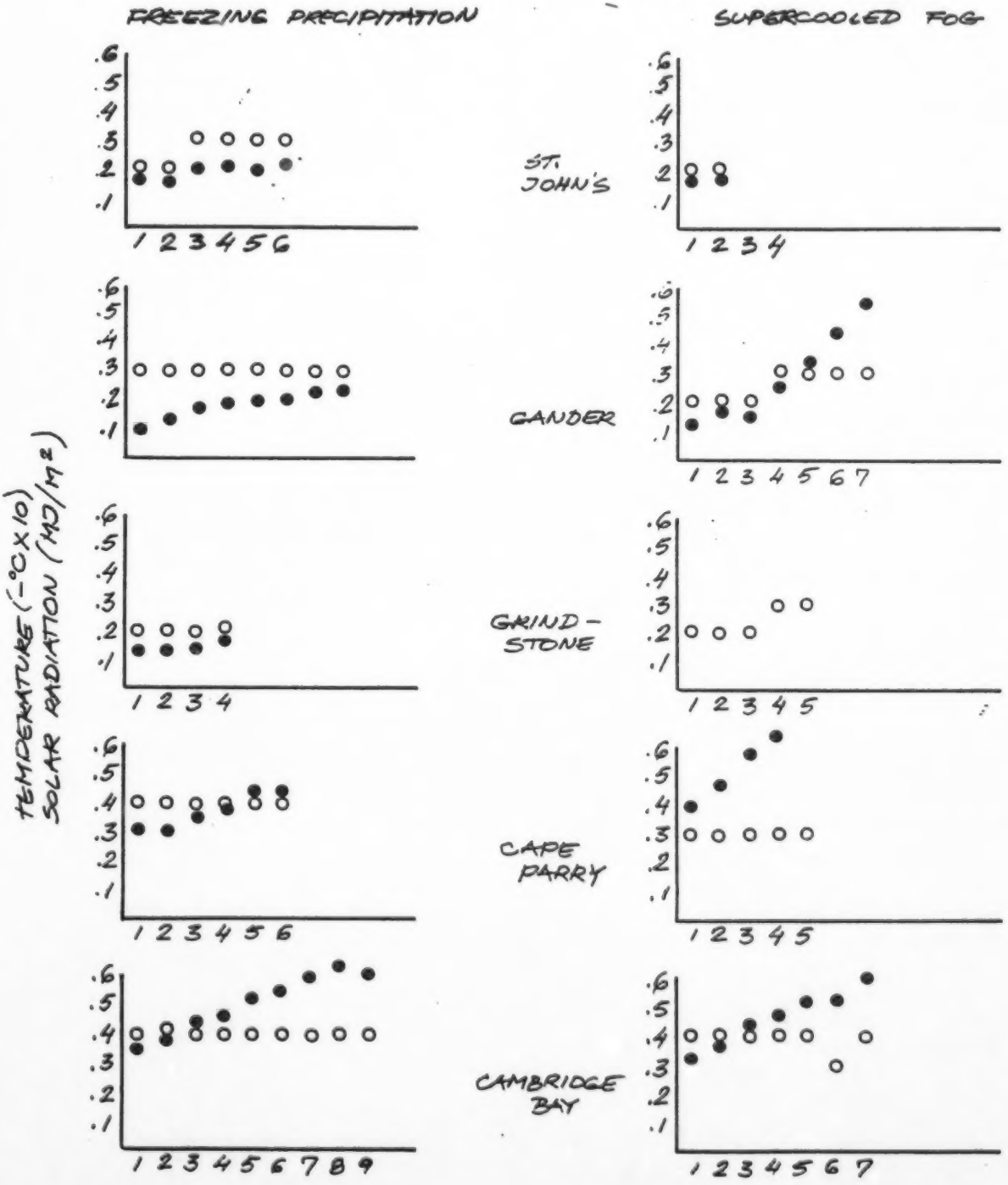
Location	Percent of Annual Average Wind Density											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
St. John's	11	29	28	11	*	*	0	0	0	0	1	20
Gander	20	11	25	25	*	*	0	0	0	7	2	10
Daniels Harbour	5	34	12	31	*	0	0	0	0	0	0	18
Stephenville	8	11	28	53	0	0	0	0	0	0	0	0
Sydney	26	3	27	17	9	0	0	0	0	0	0	18
Yarmouth	18	27	30	*	*	0	0	0	0	0	0	25
Chatam	3	21	13	10	*	0	0	0	*	*	53	*
Summerside	11	23	43	21	0	0	0	0	0	0	0	2
Grindstone	17	12	37	33	*	0	0	0	0	0	0	1
Sept-Iles	10	5	11	25	3	0	0	0	0	*	18	28
Kuujjuarapik	0	0	5	17	13	1	*	0	0	1	38	24
Yellowknife	0	*	8	2	1	0	0	0	0	44	35	10
Baker Lake	0	0	0	2	40	0	0	0	0	52	2	4
Hall Beach	0	0	0	0	14	4	*	*	24	58	*	*
Cape Parry	0	0	*	3	39	11	1	9	3	31	3	0
Cambridge Bay	0	0	0	1	19	27	0	0	28	22	2	0
Frobisher Bay	0	2	0	0	72	*	*	0	0	18	8	*
Burwash	0	1	0	9	18	0	0	*	0	1	71	0
Thompson	0	*	6	5	9	1	0	0	*	37	24	18
Nitchequon	0	0	7	32	14	5	0	0	0	7	35	*
Big Trout Lake	0	0	9	9	9	0	0	0	1	15	56	*
Smithers	4	22	3	0	0	0	0	0	*	5	21	45
Prince Rupert	15	15	2	0	0	0	0	0	0	*	8	60
Abbotsford	32	9	*	0	0	0	0	0	0	1	7	51
Port Hardy	4	*	0	0	0	0	0	0	0	0	96	0

remain below freezing, hourly global solar radiation is normally in the range of 0.10 to 0.20 for the Maritime locations and greater than 0.30 MJ/m^2 for the Arctic locations. Air temperatures average from -2 to -3°C at the Maritime stations and -4°C at the Arctic stations. After supercooled fogs, solar radiation and air temperatures are similar to that of freezing precipitation, although solar radiation may be somewhat greater. Figure 3 provides the mean solar radiation and air temperatures for the median duration of these events at the five locations mentioned above.

FIGURE 3

SOLAR RADIATION AFTER FREEZING PRECIPITATION OR SUPERCOOLED FOG AT SELECTED STATIONS

● SOLAR RADIATION ○ AIR TEMPERATURE



4.0 DISCUSSION OF RESULTS

4.1 POTENTIAL WIND ENERGY LOSS

This preliminary investigation of potential power loss due to icing have indicated that up to 10 percent of potential available energy could be affected by icing. Of the 25 locations investigated, ten had potential power losses of 4 percent or more. This is however a conservatively low figure for a number of reasons:

observations are from locations not representative of higher altitudes
weather observations are only representative of the near surface layer of 10 m above ground level
measured wind data may not be accurate due to icing of the anemometer

Altitude Effects

With regard to the first point, areas with the highest icing potential are not well represented by weather observing stations in the Atmospheric Environment Service network. Even where an observing station is close to an area of interest, topographical effects can greatly modify ice accretion severity over small distances.

There are locations, where icing is so severe and residence time so long that installation of a WECS would not be practical. Extremely heavy icing can be expected at higher elevations along the St. Lawrence Valley and along the coasts. The following paragraphs provide some examples to indicate the potential impracticality and problems of locating WECS at high elevations in certain regions of the country.

Observations at Mont Sutton in Quebec provide an indication of the frequency that higher elevations may be immersed in cloud (Schemenauer, 1986). For example during January 1986, the summit of Mont Sutton (elevation 970 m) was in cloud 65 percent of the time at 0800 EST and 48 percent during the period from 1200 to sunset. Under these conditions, a rime ice deposit could conceivably grow as well as persist throughout the month.

Felin (1976) provides some examples of damaging ice events in Quebec caused by locating transmission lines in exposed and elevated areas. In November 1969, twenty-nine towers on Mont Elie, collapsed due to ice loads. The site of the accident was approximately 900 metres above sea level and the first mountain to intercept the humid air coming from the Gulf of St. Lawrence. The response to the accident was to reconstruct the line to pass at

the foot of Mont Elie.

Variation of Meteorological Parameters Above the Surface

The variation of icing with height at one site can be illustrated with observations made in Sweden by Gustafsson et al. (1982). During a winter period of two months 9-hours of icing were detected at the 10-m level and 76 hours were detected at the 75-m level. For inland fogs, one would also expect a substantial increase of liquid water content with height above ground (i.e Pinnick et al., 1978).

Accumulation of rime ice would also vary with WECS height due to the increase in wind speed with height. Thus for large WECS installations one would expect both an increased incidence of icing and more severe icing than obtained from surface meteorological information in areas prone to in-cloud icing.

Anemometer Icing

Finally, icing of anemometers may cause a decrease in observed windspeed which would translate into a smaller indication of potential wind energy lost than actually occurs. This will also be included in the total potential available wind energy but will be of greater importance for just the icing conditions.

Seasonal Aspects of Potential Wind Energy Loss Due to Icing

An additional consideration is the seasonality of potential wind energy loss due to icing. At most locations, more than 50 % of the potential power loss from icing occurs in two months. Up to 20 percent of the time could be affected by ice in these months. In other words, WECS power loss or reduction could be dramatic in the peak icing months at the locations most susceptible to icing.

4.2 ICE RESIDENCE TIME

The length of time that ice remains on a WECS after an icing event is important, since it directly affects the potential downtime and the probability of encountering a high wind speed. There are very few observations of residence times of ice. Extreme durations of icing noted in the literature include 8 days for glaze ice in Iowa (Bennett, 1955) and six weeks for ice that formed during a storm in the Upper Connecticut Valley of the United States (Bendell and Paton, 1981).

Duration of ice is highly dependent on local temperatures and geographical location. In this study the maximum duration was limited to 10 days due to computing restrictions. There were two

locations where the maximum was encountered. Fort Chimo had 10 240-hr periods after freezing precipitation and 13 after supercooled fog while one 240-hr period after supercooled fog was recorded for Cape Parry. It was at first, somewhat surprising to encounter so few occurrences of below freezing periods of 10 days or longer considering the observations in the United States. However, icing occurs frequently only in seasons where the temperature is in the vicinity of 0°C and thus there is some opportunity for the temperature to climb above zero in a relatively short time period even for Arctic stations.

4.3 SOLAR RADIATIONAL HEATING

The rough estimate of energy required to melt 1 mm of ice on a WECS turbine, provided in Section 2, was 0.2 MJ/m^2 for a black coated blade and 2 MJ/m^2 for aluminum . In all cases analyzed, there appears to be sufficient solar radiation to melt thin layers of ice within a few hours if the WECS has a black coated blade. For the aluminum blade, the results are marginal since a much longer period of time is required.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Analyses of climatological data pertaining to icing has indicated possible difficulties in operating WECS in certain areas of Canada. These areas include parts of the Maritimes, and the Arctic coastal regions. The major concern is the loss or reduction of power due to substantial residence time of accreted ice. While the mean duration of a freezing precipitation event is 2 to 3 hours, the temperature often remains below zero after the event for mean durations usually in the range of 10 to 20 hours. A similar situation exists for supercooled fog.

Mean solar radiation data compiled for periods of freezing temperatures after an icing storm indicate that sufficient energy is available on average to melt thin layers of ice within a few hours if the blade of a WECS is painted black.

The results are not indicative of the conditions to be found at elevations higher than the selected weather station locations where a much higher frequency of occurrence and persistence of icing would be expected.

5.2 RECOMMENDATIONS

The recommendations of this study are directed towards WECS operation and to further investigations. The results of this pilot study indicate that there is the potential for wind energy to be severely limited during icing seasons in some areas of Canada. In locating a wind turbine, careful consideration should be given to the icing conditions in the region and the seasonal variation of these conditions. This study has investigated only a limited number of stations and has revealed potential problem areas. An obvious extension of this project is the analysis of upper air data for meterological stations in ice-prone regions of the country. This would provide a first quantitative estimate of the increased frequency and persistence of icing with altitude.

Furthur investigations could be conducted but obtaining actual ice accretion information from an operating wind turbine is preferable. In this study, certain assumptions have been made regarding how much icing would affect WECS performance. There is a need to obtain quantitative data if icing degradation is to be accounted for in providing WECS designs for isolated or elevated areas. Cooperation with research conducted by the electrical utilities could be beneficial in delineating icing problems with respect to WECS.

In point form, recomendations stemming from this study are:

(i) to extend this analysis to upper air stations in selected regions of Canada to provide an indication of the altitude hazard of icing

(ii) to collect data on a WECS in an ice prone area

(iii) to develop a methodology (i.e. icing model) where the performance degradation of a WECS can be incorporated in a wind resource assessment

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APPENDIX I

APPENDIX I - TABLE 1

SOLAR RADIATION (MJ/m^2) AFTER FREEZING PRECIPITATION EVENT

	Median Length(hr)	Hour After Freezing Precipitation Event 1	2	3	4	5	6	7	8	9	10	11	12
St. John's	6	.19	.17	.20	.21	.20	.21						
Gander	8	.10	.12	.16	.18	.20	.21	.23	.23				
Daniels Harbour	4	.14	.11	.11	.08								
Stephenville	3	.13	.19	.21									
Sydney	5	.14	.19	.22	.24	.21							
Yarmouth	5	.10	.14	.18	.23	.31							
Chatam	4	.10	.15	.18	.23								
Summerside	4	.10	.11	.15	.18								
Grindstone	4	.14	.14	.14	.20								
Sept-Iles	4	.15	.21	.24	.20								
Fort Chimo (Kuujjuaq)	10	.13	.15	.15	.16	.20	.19	.21	.24	.29	.28		
Kuujjuarapik	10	.25	.32	.37	.40	.42	.46	.51	.39	.39	.40		
Yellowknife	11	.07	.06	.06	.08	.09	.12	.14	.14	.14	.14	.16	
Baker Lake	8	.29	.34	.39	.44	.43	.46	.51	.52				
Hall Beach	8	.35	.38	.44	.49	.50	.50	.55	.58				
Cape Parry	6	.30	.30	.36	.40	.45	.44						
Cambridge Bay	9	.33	.39	.42	.47	.52	.54	.60	.62	.59			
Frobisher Bay	10	.08	.13	.16	.25	.30	.24	.19	.21	.23	.15		
Burwash	23	.09	.07	.04	.09	.09	.10	.12	.11	.09	.09	.09	
Thompson	7	.23	.29	.23	.16	.10	.09	.13					
Nitchequon	8	.21	.24	.26	.28	.28	.26	.25	.29				
Big Trout Lake	6	.15	.18	.20	.18	.20	.19						
Smithers	9	.05	.09	.15	.11	.09	.08	.07	.05	.07			
Prince Rupert	2	0	0										
Abbotsford	2	.08	.09										
Port Hardy	3	0	0	0	(1 event only)								

APPENDIX I - TABLE 2

AIR TEMPERATURE (°C) AFTER FREEZING PRECIPITATION EVENT

	Median Length(hr)	Hour After Freezing Precipitation Event											
		1	2	3	4	5	6	7	8	9	10	11	12
St. John's	6	- 2	- 2	- 3	- 3	- 3	- 3						
Gander	8	- 3	- 3	- 3	- 3	- 3	- 3	- 3	- 3				
Daniels Harbour	4	- 3	- 3	- 3	- 3								
Stephenville	3	- 2	- 2	- 2									
Sydney	5	- 2	- 2	- 2	- 2	- 3							
Yarmouth	5	- 3	- 3	- 3	- 3	- 3							
Chatam	4	- 3	- 3	- 3	- 3	- 3							
Summerside	4	- 2	- 3	- 3	- 3								
Grindstone	4	- 2	- 2	- 2	- 2								
Sept-Iles	4	- 2	- 3	- 3	- 3								
Fort Chimo (Kuujuaq)	10	- 3	- 3	- 4	- 4	- 4	- 4	- 4	- 5	- 5	- 5		
Kuujjuarapik	10	- 3	- 3	- 4	- 4	- 4	- 4	- 4	- 4	- 5	- 5		
Yellowknife	11	- 5	- 5	- 5	- 5	- 5	- 5	- 5	- 5	- 5	- 5	- 5	
Baker Lake	8	- 4	- 4	- 4	- 4	- 4	- 4	- 4	- 4				
Hall Beach	8	- 3	- 3	- 3	- 3	- 3	- 3	- 3	- 3				
Cape Parry	6	- 4	- 4	- 4	- 4	- 4	- 4						
Cambridge Bay	9	- 4	- 4	- 4	- 4	- 4	- 4	- 4	- 4	- 4			
Frobisher Bay	10	- 3	- 3	- 3	- 3	- 3	- 3	- 3	- 3	- 3	- 3		
Burwash	23	- 5	- 5	- 5	- 5	- 5	- 5	- 5	- 5	- 5	- 4	- 4	- 4
Thompson	7	-11	-11	-11	-11	-12	-11	-11					
Nitchequon	8	- 4	- 5	- 5	- 5	- 4	- 4	- 4	- 4				
Big Trout Lake	6	- 4	- 4	- 4	- 4	- 4	- 5						
Smithers	9	- 3	- 3	- 4	- 4	- 4	- 3	- 4	- 4	- 3			
Prince Rupert	2	- 3	- 2										
Abbotsford	2	- 2	- 2										
Port Hardy	3	- 1	- 1	- 1		(1 event only)							

APPENDIX I - TABLE 3

SOLAR RADIATION (MJ/m^2) AFTER A SUPERCOOLED FOG EVENT

	Median Length(hr)	Hour After Supercooled Fog Event								
		1	2	3	4	5	6	7	8	9
St. John's	2	.18	.20							
Gander	7	.12	.16	.21	.22	.21	.20	.17		
Daniels Harbour	7	.10	.17	.14	.27	.34	.45	.54		
Stephenville	6	.18	.21	.28	.41	.49	.41			
Sydney	4	.19	.24	.33	.35					
Yarmouth	5	.24	.15	.09	.10	.16				
Chatam	5	.27	.26	.30	.26	.18				
Summerside	9	.32	.37	.39	.36	.37	.34	.45	.44	.58
Grindstone	5	.23	.30	.34	.37	.38				
Sept-Iles	5	.18	.13	.17	.23	.23				
Fort Chimo(Kuujuaq)	6	.18	.35	.51	.63	.70	.71			
Kuujjuarapik	6	.42	.52	.58	.60	.72	.60			
Yellowknife	7	.11	.15	.18	.18	.20	.19	.11		
Baker Lake	6	.56	.66	.78	.87	.89	.84			
Hall Beach	4	.40	.50	.47	.46					
Cape Parry	5	.40	.48	.56	.63	.72				
Cambridge Bay	7	.32	.39	.42	.47	.52	.54	.60		
Frobisher Bay	6	.20	.26	.42	.52	.57	.64			
Burwash	4	.34	.38	.55	.60					
Thompson	5	.38	.36	.43	.41	.39				
Nitchequon	8	.53	.65	.50	.39	.46	.41	.38	.32	
Big Trout Lake	7	.42	.57	.54	.52	.51	.44	.53		
Smithers	2	.13	.18							
Prince Rupert	3	.09	.09	.12						
Abbotsford	4	.12	.14	.14	.12					
Port Hardy		.05	.02	.001						

APPENDIX I - TABLE 4

MEAN AIR TEMPERATURE (°C) AFTER SUPERCOOLED FOG EVENT

	Median Length(hr)	Hour After Supercooled Fog Event								
		1	2	3	4	5	6	7	8	9
St. John's	3	- 2	- 2							
Gander	7	- 2	- 2	- 2	- 3	- 3	- 3	- 3		
Daniels Harbour	7	- 1	- 1	- 1	- 2	- 2	- 2	- 2		
Stephenville	6	- 3	- 2	- 2	- 2	- 2	- 2			
Sydney	4	- 2	- 2	- 2	- 2					
Yarmouth	5	- 2	- 3	- 3	- 3	- 3				
Chatam	5	- 4	- 4	- 3	- 3	- 3				
Summerside	9	- 3	- 3	- 3	- 3	- 3	- 3	- 4	- 4	- 4
Grindstone	5	- 2	- 2	- 2	- 3	- 3				
Sept-Iles	5	- 3	- 3	- 3	- 3	- 3				
Fort Chimo (Kuujuaq)	6	- 9	- 9	- 9	-10	-10	-10			
Kuujjuarapik	6	- 3	- 4	- 4	- 4	- 3	- 4			
Yellowknife	7	- 4	- 4	- 4	- 4	- 4	- 4	- 4		
Baker Lake	6	- 4	- 4	- 3	- 3	- 3	- 3			
Hall Beach	4	- 4	- 4	- 3	- 3					
Cape Parry	5	- 3	- 3	- 3	- 3	- 3				
Cambridge Bay	7	- 4	- 4	- 4	- 4	- 4	- 3	- 4		
Frobisher Bay	6	- 3	- 4	- 4	- 4	- 4	- 4			
Burwash	4	- 6	- 6	- 4	- 5					
Thompson	5	- 8	- 9	- 8	- 7	- 7				
Hitchequon	8	- 4	- 4	- 4	- 4	- 4	- 5	- 5	- 5	
Big Trout Lake	7	- 4	- 3	- 3	- 3	- 3	- 3	- 3		
Smithers	2	- 3	- 3							
Prince Rupert	3	- 2	- 2	- 2						
Abbotsford	4	- 3	- 2	- 3	- 2					
Port Hardy	3	- 1	- 1	- 1						